Chapter 26
Macroscale Applications in Tribology

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Abstract This chapter addresses some of the basic mechanical and chemical issues affecting tribology in a broad range of macroscale applications such as space; automotive; rail transport; earthmoving, mining, and mineral processing; marine equipment; and gas and steam turbines. Many of the featured system's successes rely on understanding and solving tribological issues involving friction, lubrication, and wear of mating components. In many instances, solutions require a multidisciplinary approach to achieve the desired efficiency, reliability, compliance, and safety necessary to ensure economical and feasible operation. The presented topics were chosen to illustrate the broad range and importance that tribology plays beyond the traditional industrial and manufacturing applications, as well as to illustrate the numerous encounters of tribology in our lives.

1 Space Tribology

1.1 Introduction

This section on space tribology will primarily focus on the application of lubrication mechanisms used in extraterrestrial environments where reliable performance of satellites, spacecraft, and space stations is the principal concern. Space tribology involves a broad range of tribological regimes from boundary lubrication to

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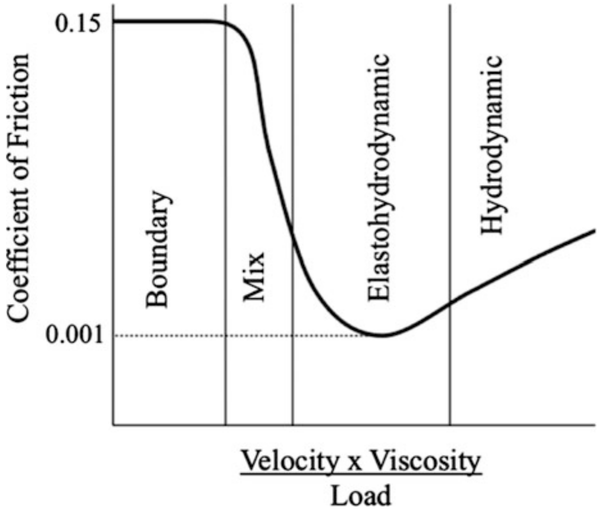
mixed, elastohydrodynamic, and hydrodynamic lubrication. Traditionally, it has been the role of tribologists to utilize lubricants based on space heritage rather than the prestige of the technology or optimization of materials. This perspective often sufficed because mission lifetimes were short and mechanical duty cycles were low. As space exploration has developed, mission lifetimes began increasing, resulting in more component failure in nonlubricated systems such as electronics, batteries, and computers [1]. In recent times, a shift has occurred where these auxiliary components have improved to the point where the lubricating systems are now the limiting factor depleting spacecraft reliability and performance. Although tribological systems are relatively inexpensive in comparison to the rest of the spacecraft and its components, the importance of such systems plays a crucial role in the operational compliance of spacecraft, and their singular failure can potentially render a spacecraft or satellite inoperable [2]. An example of a narrow margin for an expensive tragedy is the Galileo spacecraft that was launched in 1989 from the Space Shuttle Atlantis. A vital component on Galileo was a high-gain umbrellalike antenna that was in the closed position during the launch into space. In 1991, after the Galileo spacecraft was released from the Atlantis shuttle, the high-gain antenna partially opened. It was later determined that four of eighteen ribs had seized up and were stuck in place on the antenna because of the loss of the bonded dry film lubricant [3]. As a result, the high-gain antenna was virtually unusable, and the mission was only salvaged by the use of a secondary low-gain antenna that was able to undergo upgrades in its data transmission capabilities.

1.2 Mechanism Components

Satellites, spacecraft, and space stations have many instruments and components that require lubrication, for example, solar array drives; momentum, reaction, and filter wheels; tracking antennas; scanning devices; and various sensors. Each of these devices has unique hardware designed for a specific application that requires lubrication to prevent serious damage caused by friction and wear. As a result, a variety of lubrication regimes are present in space tribology. In all of the aforementioned tribological applications, two or more surfaces are in relative motion with one another. To protect the surfaces from unwanted wear and potential damage, a lubricant with low shear resistance that can maintain surface separation is applied to the contacting surfaces. In many space applications, these lubricants can be adsorbed gas, reaction films, and liquid or solid lubricants. Lubrication regimes are classified by the film thickness of the lubricant using a Stribeck curve [4], as shown in Fig. 26.1, that plots the coefficient of friction against the nondimensional Stribeck number [5]. The Stribeck number is composed of viscosity, speed, and load and is used to determine which lubrication regime is present.

Fig. 26.1 Friction coefficient as a function of the Stribeck number



1.3 Lubrication Regimes

Boundary lubrication is a complex regime dealing with metallurgy, surface topography, corrosion, catalysis, reaction kinetics, and physicochemical adsorption [6, 7]. Boundary lubrication takes place when the Stribeck number is low and the asperities of the two opposing surfaces come into contact. In this regime, the asperity contacts support much of the applied load, and there is minimal thin-film lubrication. As for this reason, it is important in boundary lubrication that there is a formation of a protective surface film to minimize the wear and damage to the surfaces. As the Stribeck number increases, the mixed lubrication (ML) regime begins to occur, where both asperity contacts and fluid film effects take place. The elastohydrodynamic (EHL) regime follows where high loads can cause elastic deformation of the surfaces and the pressure-viscosity effects of the lubricant dominant over asperity contacts. As the Stribeck number enters the region of high viscosities, high speeds, and low loads, the surfaces become completely separated by a thick lubricant film; this is the hydrodynamic (HD) regime. In this regime, friction is determined by the rheology of the lubricants, and as shown in Fig. 26.1, the friction coefficient tends to increase in comparison to the mixed or elastohydrodynamic regimes.

1.4 Gyroscopes

The occurrences of the aforementioned lubrication regimes occurring in a spacecraft often take place in many of the gyroscope applications. Gyroscopes (Fig. 26.2) such as gimbal are designed for relatively low-speed applications,

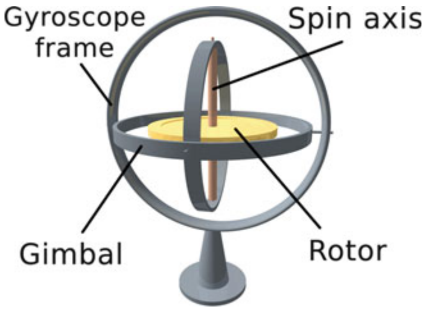


Fig. 26.2 3D gyroscope schematic [75]

and the bearings involved operate in the boundary regime. Other gyroscopes that measure changes in orientation with high precision have been shown to operate in the hydrodynamic regime with speeds upwards from 8,000 to 20,000 RPM. Within a gyroscope, the bearing is the critical component and fluctuations in the bearing reaction cause torque, noise, and excess heat generation that can have an ill effect on the determination of the zero position of the gyroscope, rendering it inept [8].

1.5 Momentum and Reaction Wheels

Momentum and reaction wheels are flywheels (Fig. 26.3) used to provide attitude control authority and stability on spacecraft [9]. They operate by adding or removing energy from the flywheel by applying torque to a single axis of the spacecraft, causing it to react by rotating. Stability about a single axis arises by maintaining the flywheel rotation or momentum. Through coordination of multiple momentum or reaction wheels, full three-axis attitude control and stability can be achieved [10]. Momentum wheels operate at speeds from 3,000 to 10,000 RPM (i.e., hydrodynamic regime), whereas reaction wheels operate at lower speeds and remain in the mixed lubrication regime. The majority of the problems that lead to failures with these wheels are a result of inadequate lubrication, loss of lubrication, and lubricating degradation [8]. Due to the high speeds in the momentum wheels, the lubricants are subjected to higher operating temperatures. This makes the lubricant susceptible to increases in creep or accelerated degradation. Solutions for the momentum wheels have been to incorporate a lubricant circulation system, lubricant impregnation retainers, labyrinth seals, barrier coatings, or the use of synthetic lubricants. When utilizing reaction wheels, tribologists and lubrication engineers primarily focus on supplying them with lubricants having excellent boundary lubrication characteristics that create a sustainable protective surface film to minimize the wear and damage to the surfaces in the support bearings.

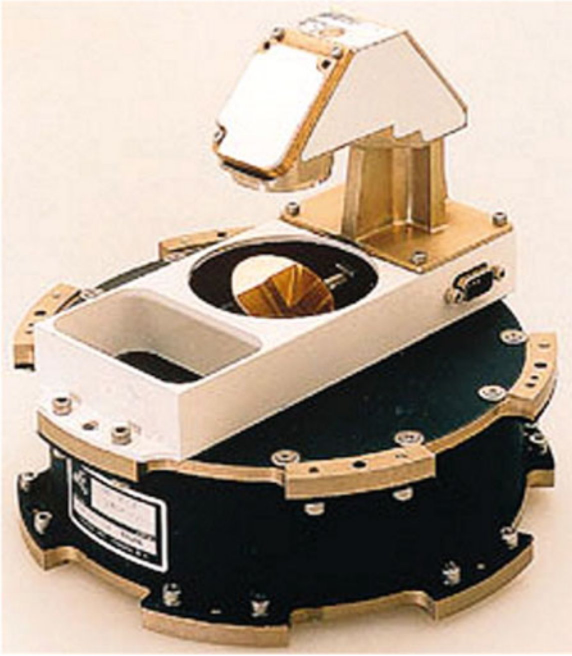


Fig. 26.3 A momentum/reaction wheel comprising a high-accuracy Conical Earth Sensor to maintain a satellite's precise attitude [9]

1.6 Control Momentum Gyroscope

A control momentum gyroscope (CMG) is an attitude control device that incorporates aspects of the gyroscope and the momentum wheel through a spinning rotor and multiple motorized gimbals that can shift a rotor's angular momentum. As a result of the rotor tilting, the angular momentum causes a gyroscopic torque that rotates the spacecraft allowing it to stabilize the spacecraft's attitude control system. Control momentum gyroscopes are currently used on the International Space Station for stabilization. In their use, similar design considerations to that of the gyroscope and momentum wheels must be included when selecting an appropriate lubricant that could possibly operate in the full spectrum of lubrication regimes [8]. Figure 26.4 shows Boeing technicians removing the cover from a CMG in the Space Station Processing Facility at the Kennedy Space Center [11, 12].

1.7 Attitude Control Sensors

Another instrument that aids in the attitude control system in spacecraft is scanning or rotating sensors. One example is the scanning horizon sensor that detects the Earth's horizon allowing for a spacecraft to orientate itself. These sensors require lubrication of the bearing components to ensure the accuracy, operational lifetime, and reliability of the sensor throughout the entire mission lifetime. Failure in the

Fig. 26.4 NASA personnel handle a single control moment gyroscope for the International Space Station [12]

lubricant by contamination or evaporation would lead to a lack of sensory information that would adversely affect the spacecraft's systems that rely on horizon-sensor-derived information such as the orientation of instruments and antennas. The bearings within these systems have moderate operational speeds from 400 to 1,600 RPM with minimal loading, therefore allowing a lubricant to operate in the boundary lubrication regime [2]. Some scanning sensors such as the Gemini horizon sensor use azimuth-scan edge tracking with a single field of view to track a planet's horizon. In this sensor, the scanning head oscillates over the azimuth-scan angle as shown in Fig. 26.5 [13]. This oscillatory motion, in conjunction with the rotation in the azimuth-scan angle, places higher demand on the lubricant. As a result of the small oscillatory angle, no new lubricant flows back into the contact zone of the scanning head. This places greater importance on the lubricant, which operates in the boundary lubrication regime, to establish a sufficient protective surface film to prevent wear and damage to the sensor [14].

1.8 Lubricants and Accelerated Life Testing

Lubricants in space applications are primarily liquid or solid, and in some instances, they can consist of adsorbed gas or reaction films. Often the choice is left up to the designer, but each type has its merits and deficiencies. Table 26.1 highlights a few of the differences between liquid and dry lubricants [15]. Liquid lubricants can consist of mineral oils, silicones, polyphenyl ethers, esters, synthetic hydrocarbons, perfluoropolyethers, and silahydrocarbons. Dry lubricants are lamellar solids such as

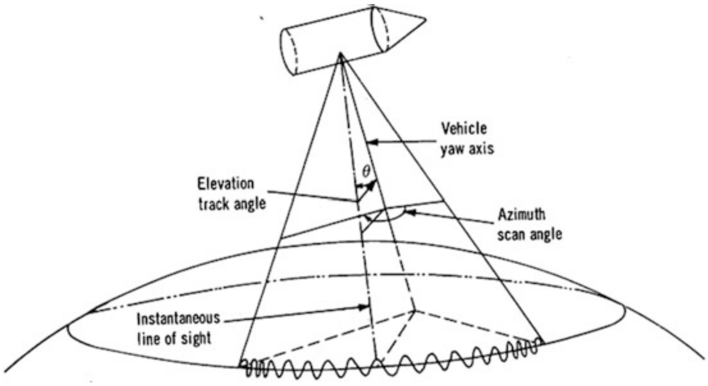


Fig. 26.5 Azimuth-scanning geometry [13]

Table 26.1 Comparison of liquid and dry lubricants [15]

Liquid lubricant	Dry lubricant
Finite vapor pressure	Negligible vapor pressure
Viscosity, creep, and vapor pressure, all temperature dependent	Wide operating temperature
Sealing required	Negligible surface migration
Invalid accelerated testing	Valid accelerated testing
Insensitive to air or vacuum	Short life in moist air
Low frictional noise	Debris causes frictional noise
Friction speed dependent	Friction speed independent
Life determined by lubricant degradation	Life determined by lubricant wear
High thermal conductance	Poor thermal characteristics
Electrically insulating	Electrically conductive

molybdenum disulfide and tungsten disulfide; soft metals including lead, gold, silver, or indium; and polymers consisting of polyimides and polytetrafluoroethylene [2].

Due to the importance of lubricants to sustain the desired performance of the spacecraft, they must undergo extensive ground-based testing to ensure that they will meet the cycle and operational condition requirements for current and possibly future space missions. Two approaches are used to qualify the performance of a lubricant; the first is system-level tests on actual flight hardware and the second is laboratory tests to simulate actual operational conditions that the lubricant would experience in an actual flight system [8]. The first method is economically infeasible and impractical to test for all lubricants used throughout a spacecraft; therefore, the second method is the common practice. One of the premier laboratory tests is accelerated life tests, where lubricants are easily tested and monitored providing fast and reliable qualitative results. Often these tests are indicative of lubricant characterization by subjecting a lubricant to similar operational conditions it would

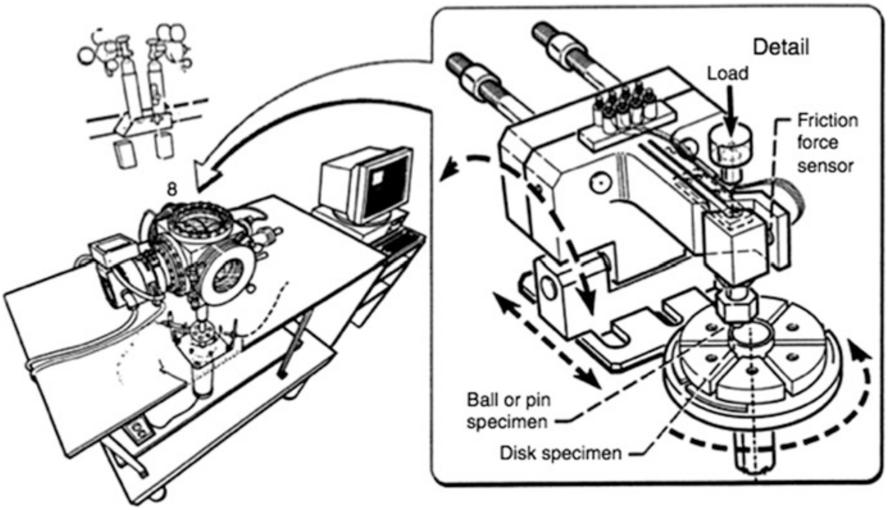


Fig. 26.6 Ultra-high-vacuum pin-on-disk tribometer [21]

experience in the field [16]. Additionally, data from these tests can be used to enhance the lubricant or additive design allowing for a baseline data set to be generated. In accelerating life tests, various test parameters such as speed, load, temperature, contaminants, quantity of lubricant available, and surface roughness are all varied to gauge the reliability of a lubricant [17]. Although these tests provide immediate results, they cannot accurately predict properties that evolve with time such as lubricant creep, lubricant loss through evaporation or centrifugal forces, and lubricant degradation [16]. Accelerated life tests are often conducted using tribometers that can come in a variety of designs. There are primarily four types of testing apparatuses used: (1) an eccentric bearing test apparatus [8], (2) a spiral orbital rolling contact tribometer (SOT) based on the design of a thrust bearing [18, 19], (3) a vacuum four-ball tribometer designed to test liquid lubricants under purely sliding conditions [20], and (4) a vacuum pin-on-disk tribometer for testing solid film coatings as shown in Fig. 26.6 [21].

1.9 Conclusion

Space tribology is an integral aspect in providing spacecraft, satellite, or space station performance. Although it can often be overlooked, examining the consequences of what can happen when a component or mechanism stops functioning as a result of an improperly used lubricant or the lack of using a lubricant can have serious effects on the reliability, safety, and performance of spacecraft. This section provides a brief review on the importance of lubricants in space applications, the types of lubricants used, and the testing that goes into each lubricant.

2 Automotive Tribology

2.1 Introduction

Automotive tribology is the aspect of tribology focused on automobile performance and reliability. The automobile is undisputedly the most widely used machine in the world today, with over 600 million passenger cars worldwide (approximately 1 for every 11 people) [22, 23]. In the United States, it is estimated that with only a few modifications to improve friction and minimize wear, this would result in significant reductions in fossil fuel usage with saving upwards of $120 billion per year [24, 25]. The automobile has become vital in commerce and transportation for developed and developing nations throughout the world. Automobiles consist of thousands of components with many of them relying on their surface interactions to function properly such as bearings, pistons, transmissions, clutches, gears, tires, and electrical contacts [2]. Investigating the tribological phenomena in these applications is imperative to the reliability, durability, and performance of automobiles. Many advances in lubricants, bearings, and surface topography have risen as a result of the automobile industry. An example of a less subtle tribological application within the automobile industry is the advent of the windshield wipers. Although, at first, it seems more like a trivial application, optimization of the materials, loads, pressures, and environmental conditions plays a role to the solution to this problem and is of interest to tribologists to provide a clear windshield for a driver to operate a vehicle safely. This is but one example of the many impacts tribology has made within the automotive industry. In this section, three tribological systems are investigated that are paramount to the success and ubiquitous use of the automobile: the engine, tires, and brakes. Each operates under different lubrication regimes, operating conditions, and environments, thereby making their use of lubricants, surface technology, and materials drastically different.

2.2 The Internal Combustion Engine

The reciprocating internal combustion (IC) engine has risen to popularity due to its performance, reliability, and versatility. It has quickly become the most common machine in regard to locomotion and transportation by being utilized in a vast array of vehicles such as motorcycles, scooters, mopeds, cars, vans, trucks, buses, agricultural vehicles, construction vehicles, trains, boats, ships, and airplanes [26]. Despite the broad application of IC engines, they do have major flaws such as their relatively low thermal and mechanical efficiencies, with much of the energy potential produced by fuel dissipating as heat and friction losses [26]. The most detrimental effect from the use of IC engines is their contribution to atmospheric pollution through hydrocarbons, particulate, nitrogen oxides, and carbon dioxide emissions [2]. As a result of the many hundreds of millions of IC engines in use, minimal improvements in engine efficiency, emission levels, and durability would lead to tremendous effects on the world economy directly affecting the petroleum industry. In addition, improvements to IC engines would lessen their environmental impacts by reducing their contributions to the greenhouse effect [27]. In order to reduce the friction and wear, effective lubrication of all the engine components with minimal impact on the environment must be achieved for all the various operating conditions of speed, load, temperature, and chemical reactivity. Improvements in engine performance would result in reduced fuel consumption; increased engine power output; reduced oil consumption; a reduction in harmful exhaust emissions; improved durability, reliability, and engine life; reduced maintenance requirements; and longer service intervals [2, 28].

2.3 Lubrication Regimes

Within the engine, the three major components that contribute to an increase in friction and a decrease in efficiency are the engine bearings, piston assembly, and valvetrain. Each of these components is lubricated with a liquid lubricant that may operate in a different lubrication regime. In order to quantify the lubrication mechanism that is taking place within each of these multicomponent systems, a film thickness ratio parameter (as shown in 26.1) has been developed that is a function of the lubrication film thickness and the roughness of the two surfaces in relative motion. A film thickness ratio (λ) is used to quantify the regimes:

$$\lambda = \frac{h}{\left(\sigma^2_{surface1} + \sigma^2_{surface2}\right)^{1/2}} \tag{26.1}$$

In (26.1), h is the lubricant film thickness calculated through traditional thin-film analysis by the Reynolds equation, and σ is the root-mean-square of the roughness of the two contacting surfaces. To quantify which lubrication regime is taking place, Fig. 26.7 illustrates how the film thickness ratio can be used. Similar to the lubrication regimes present in space tribology, the first regime is the boundary lubrication where the surfaces are in contact and emphasis is put on the lubricant to produce a thin protective film to subdue wear and prevent damage to the surfaces. The mixed and elastohydrodynamic regions are where a fluid film develops limiting the amount of contact between the asperities on the surfaces. The last regime is the hydrodynamic lubrication regime where a thick film prevents the surfaces from contacting one another. In many of the components in an automobile, they may experience multiple lubrication regimes within one cycle, thus stressing the importance of understanding the different lubrication modes to achieve the desired performance levels.

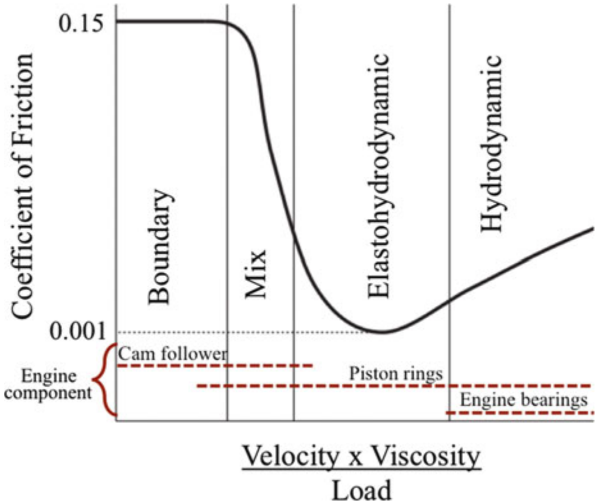


Fig. 26.7 Relationship between friction coefficient and oil film thickness ratio for engine components

2.4 Engine Components

Engine bearings generally consist of rotating journal bearings that operate in the hydrodynamic lubrication regime where the bearing surfaces are separated by a thick film. However, at low speeds, low viscosities, and high loads, this can cause increased metal-to-metal contact to occur. Journal bearings in an engine are typically used to support the camshaft, crankshaft, and connecting rods. Inspecting the tribodynamics of a journal bearing, there are many complicated issues that must be addressed with the lubricant such as the lubricant supply, thermal effects, dynamic loading, and elasticity of the bounding solids [2].

The piston assembly is the vital link in transforming the energy created by the combustion of the fuel-air mixture into mechanical energy that is used to drive the vehicle. The tribological importance of the piston is to provide an effective gas seal between the combustion chamber and the crankcase. This is done by a series of metallic rings carried by the piston that creates a labyrinth seal. Throughout a piston cycle, the rings can experience large, rapid, dynamic variations at various loads, speeds, temperatures, and lubricant availability. Examining the piston ring-cylinder wall interface, boundary, mixed, and hydrodynamic lubrication regimes can be experienced [29].

The valvetrain is a system of many components including valves, valve springs, valve spring retainers, valve keys, rocker arms, piston rods, lifter (tappets), and a camshaft. The valvetrain's primary function is to transform the rotary camshaft motion into a linear valve motion in order to control the fluid flow into and out of the combustion chamber. A secondary function is to control the auxiliary devices such as distributors, fuel pumps, water pumps, and power steering pumps. There are many mechanisms used to transmit the motion of the camshaft to the valvetrain. The most often used mechanism is the roller follower that utilizes a rolling motion to transmit the required motion allowing for lower friction. Other less frequent mechanisms include the finger follower and direct acting bucket follower. These two mechanisms operate by means of a sliding motion resulting in higher friction than the roller follower. For tribologists, the most critical interface in the valvetrain is the cam and follower due to the problem of providing effective lubrication. Often, it was assumed that the cam and follower operated in the boundary lubrication regime; however, more recent investigations have shown that mixed and elastohydrodynamic lubrications are the dominant regime [30].

2.5 The Tire

Within automotive tribology, the tire has received extensive scrutiny over the years because of its importance for retaining traction while driving. A tire is a protected cover for the compressed air toroidal tube that is attached to the steel rim or wheel in an automobile. The tire has six functions as follows [31]:

- To allow relatively free and frictionless motion of the vehicle by means of rolling
- To avoid excessive stress in the wheel and road by distributing the vehicle weight over a substantial area of the ground surface
- To cushion the vehicle against road shocks such as bumps, potholes, and debris
- To efficiently transmit engine torque to the road surface with little power loss
- To provide adequate braking, driving, and steering loads through tire adhesion
- To ensure lateral and directional stability

The construction of a tire casting and rubber ply layout is important to the load-carrying capacity, lifecycle, steering characteristics, resistance to damage, ride quality, and noise. Radial plies are the more common ply among passenger cars and trucks [32]. The outer portion of the tire is made up of a patterned rubber tread that is vital to the tribological interaction between the road and the tire. The treads can be various styles as shown in Fig. 26.8 and are optimized for different driving circumstances. The purpose of the tread is to squeeze and channel water out of the contact zone to prohibit skidding or hydroplaning. In wet conditions, a fluid film can develop between the contact area of the tire and the road. This contact area can be divided into three zones as shown in Fig. 26.9. The first zone is a purely hydrodynamic area with complete separation between the tire and the road. Zone 2 is a mixed or elastohydrodynamic area where the fluid film thickness decreases to zero permitting partial contact between the tire and the road. The third zone is a boundary area where the fluid has been squeezed out through the plies and the tire is in full contact with the road. From a safety standpoint, zone 3 is the only zone that ensures sufficient frictional traction for driving, steering, and braking. When driving at high speeds and when zone 3 becomes absent, a dangerous scenario can occur. Here, the tire is no longer contacting the ground, but riding on a thin fluid film with inadequate frictional traction, which is known as hydroplaning. Hydroplaning is one of the major reasons for automobile crashes because the tire can no longer adhere to

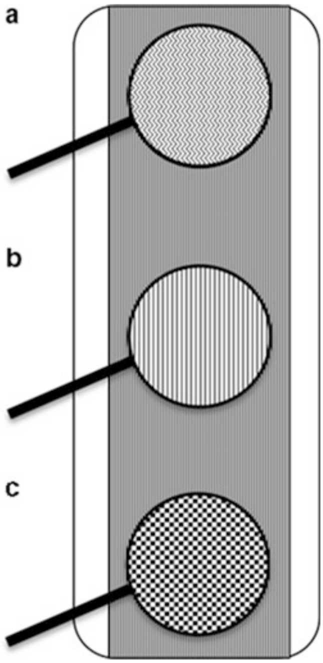


Fig. 26.8 Three basic tire tread pattern designs: (**a**) zigzag; (**b**) ribbed; (**c**) block pattern

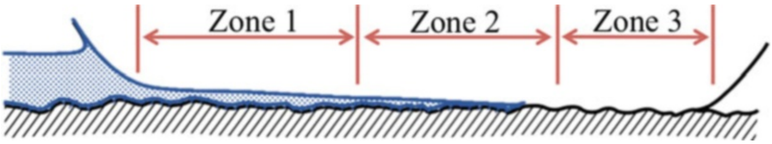


Fig. 26.9 Hydroplaning contact area zones

the pavement resulting in a disastrous driving, steering, and braking situation that can lead to serious injury or even death in the event of a collision. Investigation into the tire dynamics is often difficult because the influencing parameters such as tire design, pavement design, tire construction, tread composition, tire load, inflation pressure, vehicle speed, driving style, ambient temperature, and weather conditions can be variably different from each vehicle, person, or driving location [2].

2.6 The Brakes

Another tribological application that is vital to the performance of a vehicle is the brakes. Brakes can be either drum or disk as shown in Fig. 26.10, and they typically operate by dissipating mechanical energy by means of friction. In some energy-

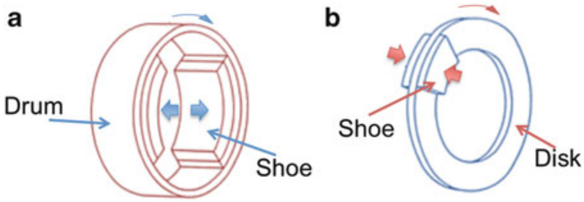


Fig. 26.10 Vehicle brake types: (**a**) drum brakes; (**b**) disk brakes

conscious vehicles, regenerative braking systems are used that convert the mechanical energy in the vehicle into rotational kinetic energy for later use to accelerate the vehicle after breaking. Traditional braking methods utilize a drum brake that applies a normal force by means of a shoe to the drum circumferential area or in the case of a disk brake to the exterior circumferential area as depicted in Fig. 26.10. The main concern for tribologists is the utilization of materials that can provide high coefficients of friction with low wear rates as well as endure the frictional heating that can occur as a result of the dissipation of the mechanical energy. During the braking process, frictional heating can cause brakes to reach temperatures upwards to a few hundred degrees Celsius with asperity flash temperatures reaching beyond 1,000 °C [31, 33]. When considering the function of brakes, attention in the design process must take into account several factors such as thermal wear, abrasive wear, adhesion-tearing, fatigue, and macro-shear wear. These various tribological phenomena all contribute to brake degradation especially in the brake shoe which wears faster than the drum and therefore is often the component needing the most maintenance [31]. Additionally, tribologists must consider contamination in the form of water, oil, dust, and corrosion that can change the effectiveness of the braking system when choosing materials in the design process. It goes without saying that the importance of reliable brakes is vital to the continued success of automobile transportation and the safety of the public.

2.7 Conclusion

The tribological implications in IC engines and drivetrains are vast; it is estimated that in the United States, a few modifications to lower friction and wear would have tremendous reductions in fossil fuel usage and would result in the US economy saving over $120 billion per year. The continued success of automobiles throughout the world is dependent on the solution of many tribological problems from those in the engine and drivetrain to the tires and brakes. Still, there are other less subtle tribological applications that are taken for granted, such as the windshield wipers. Many of the solutions to tribological problems within the automotive industry require optimization of materials, loads, pressures, and environmental conditions to operate a vehicle safely. The impact of tribology is critical in the automotive industry, and as technology improves, new tribological problems will arise.

3 Rail Transport Tribology

3.1 Introduction

In North America, there are 25,000 locomotives, totaling to 1.4 million freight vehicles riding on 13 million wheels that travel over 170,000 miles of rail, which equates to 35 million tons of steel track [2]. For these reasons, it can be understood that the railway industry has invested more money into rails than anything else except maybe land and bridges. Protecting this investment means extending the life of the rails and wheels. For the railway industry to operate effectively and economically, it is imperative that the tribological issues associated with the wheel-rail interaction be addressed and continually improved upon. Additional tribological issues involve the diesel engine, axle bearings, dampers, and traction motor bearings. This section will focus primarily on the aspects of the wheel-rail system. At the start of the nineteenth century, mechanically powered rail transport began to develop; by the end of the century, a German physicist by the name of Heinrich Rudolf Hertz published a paper on contact mechanics titled "On the contact of elastic solids" [34]. In this publication, Hertz attempted to describe the contact of glass lenses, which ultimately gave way to Hertzian contact stresses. This interfacial contact analysis can be used to describe the contacts between the rails and wheels [35] as shown in Fig. 26.11.

Fig. 26.11 A locomotive's steel wheel rolling on a steel track in a railway system, 1920s

3.2 Wheel-Rail Interaction

Passenger trains can weigh about 30 tons, and heavy freight trains can weigh upwards to 140 tons. Each cab has eight wheels that each have an area of contact with the rail of about 300 mm^2; this corresponds to approximately the size of a penny [31]. The small surface contact area leads to extremely high stresses and fatigue in the rail. Fatigue results from the cyclic loading due to the multiplicity of four wheels per rail per cab applying the same load to the same contact area. In some severe cases, the stresses normal to the plane of contact can exceed the wheel and rail tensile strength, and at times, the shear stresses can exceed the shear yield stress. During the wheel-rail interaction, slippage can occur between the wheel and the rail causing high shear forces that result in drastic frictional heating with temperature rises reaching several hundred degrees Celsius in normal operation and peaking at over 1,000 °C in extreme operation. As a result of these conditions, the wheel-rail interaction is undisputedly one of the most vital tribological interfaces in the railway system beyond the diesel engine. Since the inception of steel, rather than iron, the wheel-rail system has remained virtually unchanged. The high loading, extreme pressures, and high wear rates taking place are often so immense that it is impressive that the wheel-rail system has been operational with much success and little downtime. To this day, no wheel or rail material has been discovered that offers superior wear or fatigue resistance and yet is economically viable. The complexity of the tribology involved in the wheel-rail system requires a deep understanding of the interactions between the materials of the wheel, rail, and any potential third-body lubricants or debris mixtures. In addition, the vehicle weight, wheel-rail interaction, wheel profile, wheel adhesion, and vehicle speed must be taken into consideration when studying the tribological influences in the wheel-rail system [2].

3.3 Wheel-Rail Contact

The rolling resistance of a locomotive is due to the material grade, acceleration resistance, aerodynamic and wind drag, bearing resistance, and wheel-rail contact resistance. From an engineering perspective, the wheel-rail contact is the only resistance that is directly affected by the choice of material and can be optimized through tribological analysis. Within the wheel-rail contact, there are several contributing factors: first, elastic deflection during rolling of the wheel on the rail surfaces; second, energy dissipation by plastic deformation; and third, surface adhesion phenomena can dissipate energy [36]. Additionally, there is plastic flow of the steel surfaces in both the wheel and the rail, which accounts for the smooth shiny appearance of wheels and rails in continuous operation. By comparison, wheels and rails that are intermittently used can become rusted in appearance from lack of use [31]. As the wear continues in the wheel and rail, the contact profile widens becoming more elliptical. Tribologists investigating the pressure distribution have adopted the three-dimensional Hertzian contact model as a basis for curved bodies in elliptical form to calculate the pressure distribution, which can be described by (26.2)

$$p = p_o\left(1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}\right)^{1/2} \tag{26.2}$$

where p_o is the maximum pressure at the center of the contact, a and b are the semiaxes of the contact area, and x and y are coordinates with their origin in the center of the contact area [2]. The maximum pressure at the center of the ellipse is given by (26.3), which is primarily a function of the weight of the wheels on the rail and the affects of the mechanical properties of the material:

$$p_o = \left(\frac{6PE^{*2}}{\pi^3 R_e^2}\right)^{1/3}\left[f\left(\frac{R'}{R''}\right)\right]^{-2/3} \tag{26.3}$$

In (26.3), P is the normal load (weight) of the wheels on the rail, E^* is the composite modulus of elasticity of the wheel and rail, R_e is the equivalent relative curvature of the wheel-rail system, and $f\left(\frac{R'}{R''}\right)$ is a function of the wheel and rail radius of curvature [35, 37]. Initial approximations indicate that the contact resistance is proportional to the length of the contact area. Therefore, to retard the widening of the contact area, materials are chosen with a high elastic modulus. Steel is the widely chosen material because it offers superior mechanical properties such as high elastic modulus, strength, ductility, and wear resistance at an economical price.

3.4 Wheel-Rail Adhesion

In the wheel-rail contact, the forces acting in the direction of the locomotive's velocity are known as the traction or brake force. The traction coefficient is equal to the traction force divided by the vertical load, which is a function of the weight of the wheels on the track and the slip ratio. The maximum traction coefficient is known as the adhesion coefficient, which is an indicator of the brake performance of a locomotive. The relationship between the traction coefficient and the slip ratio is important when analyzing the frictional heat generation and the shearing that takes place on the surfaces of the wheel and rail [38]. This relationship represented by the traction-slip curve can be divided into three segments as shown in Fig. 26.12 [39]. The first segment represents a region of linear low slip caused by isothermal shearing of a linear viscous fluid or linear elastic solid [40]. The second segment is of a nonlinear, isothermal region with nonlinear viscous elements. The third

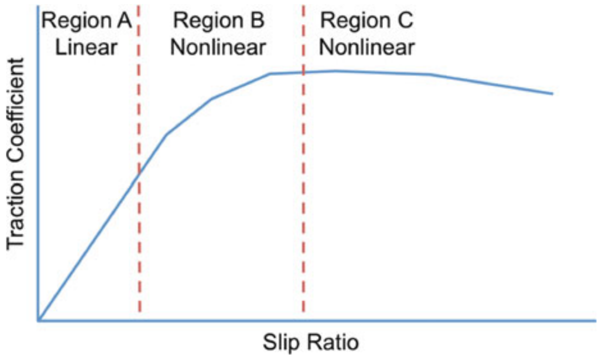


Fig. 26.12 Traction-slip curve

segment represents a region with low traction and a high degree of slippage. In this region, dissipative shearing and heat generation in the viscous film are significant. Understanding the relationship between traction and the slip ratio is an important step in understanding the tribological phenomena between the wheel and rail that aid in improving the performance of the railway system. Under high Hertzian pressure, the adhesion coefficient is independent of surface roughness, which is thought to be the result of surface asperities being heavily deformed. Another influencing effect occurs when the rails are coated with water and the locomotive is operating at high rolling speeds; the adhesion coefficient tends to decrease. This is a result of the thin fluid film building up between the wheel and the rail and thus loss of traction from lack of asperity contact. In summary, there is a delicate balance that must be maintained between the wheel-rail contacts. Suitable adhesion and traction must be present at all times in order to ensure a locomotive has adequate steering on straight and curved rails and sufficient braking performance to operate safely. However, to minimize wear of both the wheel and rail, a lubricant is incorporated into the interface, which lowers the adhesion coefficient to tolerable levels.

3.5 *Wheel-Rail Repeated Contact*

In addition to the wheel-rail adhesion, another concern for tribologists is the lifetime performance of the wheels and rails. During the course of a year, a passenger train can routinely travel 200,000 miles, about 100 million revolutions. This contributes to a significant amount of repeated sliding or rolling contacts [2]. Repeated contacts are of interest because they cyclically stress the material producing four net effects. The first is a perfectly elastic behavior whereby the contact pressure at the interface does not exceed the wheel or rail elastic limit during any load cycle. The second result takes place when plastic deformation occurs in early cycles causing a development of residual stresses and strain hardening, ultimately ending in a perfectly elastic steady-state behavior known as elastic shakedown. A third result takes the forms when no plastic deformation occurs and only a steady-state elastic-plastic behavior exists; this is known as plastic shakedown. The last result is known as ratcheting and occurs when the steady-state behavior is an open elastic-plastic loop that undergoes material accumulation and a net unidirectional stress during each cycle. In order to minimize the effects of repeated contact, tribologists try to minimize the plastic deformation which can lead to accelerated rates of wear and surface degradation. Surface engineering has led to a minimization of the plastic deformation and the shakedown by utilizing techniques such as variable hardening and surface texturing by changing the surface roughness of the material used on the wheel and rail [41–47].

3.6 Wheel-Rail Wear

Recent efforts within in the railway industry have been focused on the prevention of wear on the wheels and rails. Wear of components is the fundamental cause for replacement of most components. All railroad systems throughout the world have different criteria for removing worn rails; however, the majority of them fall within the bounds that a rail should be replaced when 30–50 % of railhead area has been removed. Rails tend to wear on the inner edge of the outer rail in curved tracks where the wheel flange initiates the contact. In straight and large radius curved tracks, the rail wear is generally vertical due to wheel tread. For the wheels, they do not necessarily need to be replaced when the flange has worn down too thin or the tread wear has left the flange too high. Wheels are traditionally re-profiled by machining when they cause a reduction in steering ability and are replaced when enough material has been lost through wear and machining that the stresses within the wheel are unacceptably high making the material a high risk for failure. Presently, four wear mechanisms occur in the wheel-rail system adhesion, abrasion, fatigue, and fretting. Adhesion takes place in the absence of a third-body lubricant or contaminant between the wheel and rail causing the metal surfaces to bond strongly to each other's asperities in contact. Due to the relative motion between the wheel and the rail, the contact interface experiences shear resulting in wear debris and damage to the rail and wheel. Abrasion occurs when the wheel or rail material hardness is significantly different enough to cause the harder material or in some instances wear debris to plow through the softer material by plastic deformation or fracture [37]. The third wear mechanism is fatigue; this arises from the cyclic normal and shear stresses produced by the rolling and sliding motion of the wheel on the rail. Fatigue causes cracks to initiate and propagate through the surfaces of the wheel or rail and causes a delamination of the surfaces to occur as illustrated in Fig. 26.13. Contrary to the previous wear mechanisms that are directly responsible for the wear in the wheels and rails, fretting is a consequence of low-amplitude vibratory motion between two bodies, either the wheel and rail or the wheel or rail and any accumulated wear debris [48]. In addition, ratcheting is important because it can cause plastic deformation that can result in significant wear damage from highly sheared surface layers.

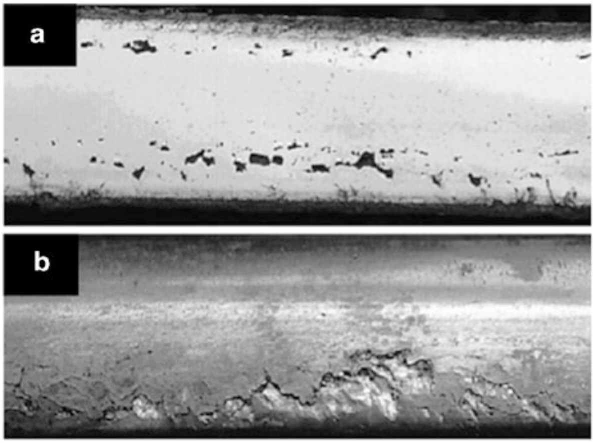


Fig. 26.13 (**a**) Low rail surface damage caused by rolling contact fatigue; (**b**) high rail surface damage caused by rolling contact fatigue

3.7 Conclusion

Railway tribology is a vital part to the sustainability of railway transport. It investigates the crucial problems that would inevitably cause deterioration in the railway network through rail deterioration, performance of bearings and current collection equipment, and the maintenance of these systems. The millions of miles of railway track around the world require important tribological issues to be addressed at the wheel-rail interface to minimize railway maintenance and to provide safe and economical railway operation. Major strides in developing materials and understanding the tribological phenomena in railway transport would lead to a better understanding of the mechanical and chemical interfaces. The focus on increasing the allowable axle and wheel loads while maintaining low wheel and rail wear and damage is necessary for the future of locomotive transportation both for industrial and commuter needs. In addition, advances in track monitoring and inspection must be at the forefront of research in order to better manage rail lifetime and extend the period between maintenance inspections.

4 Tribology of Earthmoving, Mining, and Mineral Processing

4.1 Introduction

The practices of earthmoving, mining, and mineral processing are tribologically intensive activities that involve digging, loading, hauling, crushing, handling, screening, and grinding mineral ore. These processes result in significant wear in the mechanical interaction between the metals and the abrasive mineral ore.

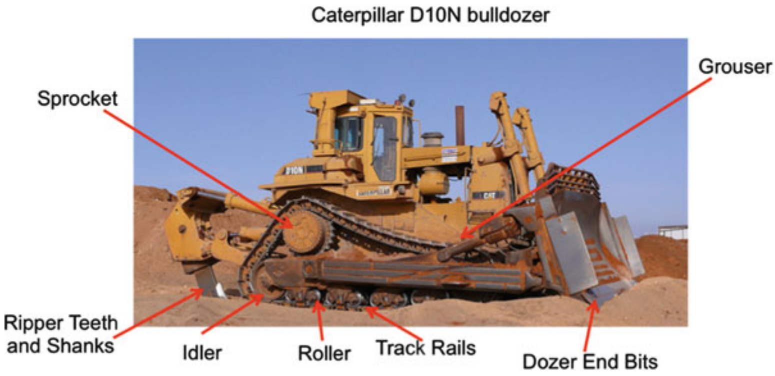


Fig. 26.14 View of a Caterpillar D10N bulldozer showing major components affected by abrasive wear [76]

The construction of a building, bridge, dam, road, or highway involves the use of earthmoving devices such as bulldozers (depicted in Fig. 26.14), scrapers, graders, excavators, front-end loaders, draglines, stripping shovels, and dump trucks. Mining and mineral processing involves the operation of digging, drilling, loading, and hauling materials using equipment such as crushers, grinders (mills), sand pumps, classifiers, flotation machines, and magnetic separators [49]. As a direct result of the operation of such machinery, there is an inherent tribological loss due to the amount of energy that is required to overcome the frictional forces. Despite the significant frictional forces, the wear loss due to the abrasion in these processes can be upwards to five times greater than the frictional losses [50] with many components on a single machine suffering from abrasive wear as shown in Fig. 26.14 with the bulldozer.

Earthmoving, mining, and mineral processing machinery makes significant use of easily replaceable, repairable, and inexpensive wear components that are very tolerable to the high wear rates. The wear mechanisms that transpire during these construction processes are complex and depend on the wear mechanism, the wear material, the nature of the abrasive material, the type of loading, and the environment [51–53]. From a tribological perspective, the interaction between the metal components and the earth demands materials that exhibit excellent ductility and work-hardening properties. For example, the transportation of ore through a chute, conveyor, and screen or the scraping of earth and gravel with a blade requires that the interacting components maintain a high surface hardness. Mining and mineral processing often operate in corrosive environments that require materials to be both wear and corrosion resistant. Through practice, tribologists and material engineers have been able to combat the wear losses, frictional resistance, and environmental demands by developing innovative materials. These materials offer superior wear, abrasion, and impact resistance that can be used in a broad range of in-service operational conditions as well as daily in excavation operations.

In the last few decades, the earthmoving, mining, and mineral processing industries have increasingly enlarged their equipment, which subsequently has led to more disastrous tribological issues involving wear, abrasion, and impact levels [53]. The growth of the equipment in these industries has been propelled by the mining industry to seek out lower-grade ores, thereby requiring a larger output of raw material while simultaneously lowering operating costs, therefore making the entire process economically feasible. As a result of the larger equipment, the quantity of material handled per unit of operation has led to more severe conditions to which wear, abrasion, and impact resistance materials must be subjected to. Additionally, emphasis is put on the importance of prolonging component lifetimes and projecting failure rates to minimize the amount of unscheduled maintenance. This is because despite all of the capital and operating costs for purchasing the equipment and other auxiliary expenses within these industries, the cost of downtime and loss in production drastically outweigh the cost of replacing worn components [50, 54, 55]. Although replacement of worn components is routine and the cost is relatively minimal, the selection of material and design of components that promote longer component lifetimes, easier installation, and lower cost remains to be important. In addition, engineers must concern themselves with the selection of materials based on availability, potential risk for catastrophic failure, and environmental considerations such as noise abatement [54]. The use of higher-cost materials and components is often restricted to two constraints. The first constraint being the use of more expensive wear-resistant materials to boost performance may in fact be cost-effective in terms of component life; however, in the macroscale, these materials ultimately drive up the capital requirements. The second constraint being the original design for much of the equipment used in these industries may not be optimal for a given process, causing it to be retrofitted later. It is for this reason that the use of expensive wear-resistant materials may not necessarily be cost-effective in the long term.

4.2 Wear Mechanisms in Mining and Mineral Processing

The tribological problems affecting earthmoving, mining, and mineral processing operations are the wear mechanisms and friction losses that cause the equipment used in these industries to expend large quantities of energy to perform their function. The wear mechanisms in these applications are affected by the properties of the wear material, the properties of the abrasive material, and the nature and severity of the interacting materials. For example, the interaction between adjacent metal surfaces, the abrasive mining materials, and the worn metal debris all contribute to the various wear mechanisms occurring. These interactions are further influenced by the size, density, and hardness of the abrasive particles, for example, if the abrasive particle is sharp and remains sharp after fracture, then cutting or gouging action of the abrasive particle will continue to abrade material from the machine components. Figure 26.15 shows the abrasive wear classification, relating the particle size to the wear mechanism [54]. The design and function of

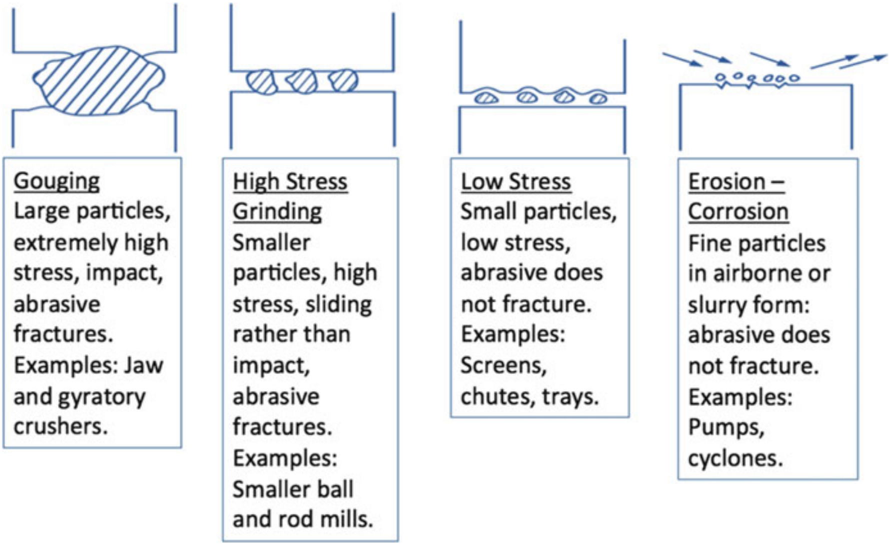


Fig. 26.15 Schematic representation of the abrasive wear classifications [54]

earthmoving, mining, and mineral processing equipment play a significant role in the quantity of wear that they experience. Earthmoving equipment experiences more abrasive wear from digging and removal of earth (such as the wear of digger teeth on a bucket excavator) than they do from scrapping operations. The wear rates exhibited in crushing and grinding operations are higher than those which occur in chute linings, screens, and classifiers, because they are more energy demanding and require greater impacts and thus increase the abrasive wear.

The abrasive wear mechanism that occurs in earthmoving, mining, and mineral processing operations can be classified into five categories as shown in Fig. 26.15: gouging and abrasion which describes the removal of large amounts of material per cycle from the wear surface; high-stress grinding abrasion (or three-body abrasion) where the abrasive particle is crushed during the wear interaction; low-stress scratching abrasion where the abrasive particle remains intact as it moves freely across the wear surface; low-stress scratching in the form of erosion; and low-stress scratching abrasion in a corrosive environment described as erosion-corrosion. As mentioned previously, the occurrence of any one of these abrasive wear mechanisms arising depends on the equipment, environmental conditions, and ore material being excavated. Table 26.2, primary tribological loss mechanisms in mining, highlights the tribological losses that occur in earthmoving, mining, and mineral processing operations [50]. It can be seen from Table 26.2 that the three-body abrasion occurs in all mining and drilling operations and is responsible for the majority of the wear to the equipment. Ore processing operations involve many tribological loss mechanisms revealing how detrimental the ore material is to components in the mining industry. Earthmoving, mining, and mineral processing operations each experience their own unique wear mechanism depending on the

Table 26.2 Primary tribological loss mechanisms in mining [50]

	Active tribological mechanism					
Operational activity	Three-body abrasion	High-stress gouging	Impact wear	High friction	Erosion	Lubricated wear
Surface mining						
Exposing and digging	X	X	X	X	–	X
Loading	X	–	X	–	–	–
Transporting	X	–	–	X	–	–
Shaft mining						
Digging	X	–	X	–	–	X
Transporting	X	–	–	X	–	X
Ore processing	X	X	X	X	X	X
Drilling						
Mud pumps	X	–	–	–	X	–
Drill pipe	X	X	–	X	X	–
Drill bits	X	X	X	–	X	–

required force levels, abrasive particle type and size, and operating or environmental factor. For these reasons, it is important to monitor the performance of components and replace worn components in order to minimize the risk of catastrophic failure.

As described, the dominant wear mechanism is abrasion; however, the secondary wear mechanism arises from metal-to-metal contact. In earthmoving, mining, and mineral processing equipment, metal-to-metal contact occurs in engines, drivetrains, connectors, bearings, and gears. In most of the equipment, the engine and drivetrains are closed off to the operational environment and wear surfaces are lubricated. However, the metal-to-metal wear is often worsened by abrasive particles due to the environmental conditions in which the machinery operates, which have the ability to cause severe problems. Discussion of the engine, drivetrain, bearings, and other components was discussed previously in this chapter and is beyond the scoop of this section.

4.3 Conclusion

In earthmoving, mining, and mineral processing, much of the research has focused on the equipment design, unit operation processes, wear-resistant materials, and repair and replacement techniques that can all be used to combat the effects of abrasion, erosion, impaction, and wear-corrosion. As the quality of ore minerals decreases, there will be a driving force for larger-scale mining operations that will necessitate new and improved materials that are energy efficient. The effort put into understanding the relationships between wear mechanisms and processes in earthmoving, mining, and mineral processing operations will facilitate the development of innovative wear, corrosion, and impact-resistant materials that will be less expensive, easy to install and repair in the field, and require less energy. Many of the tribological mechanisms involved in these industries will prove to be beneficial in other industries such as metal production, agriculture, and pulp and paper processing.

5 Tribology in Marine Equipment

5.1 Introduction

Investigations into the tribological challenges of marine equipment present a unique set of problems for tribologists in terms of fuels and lubricants used within the confines of an engine and propeller shafts. Many of the components of interest are cams, gears, chains, hydrodynamic thrust bearings, journal bearings, pistons, and rolling element bearings. The major differences in marine equipment when compared to their terrestrial counterpart is the environment and operating conditions, necessitating chemically modified fuels and lubricants to function properly under the demands of seafaring vessels. One of the issues that arise with boats, ships, tankers, and other seafaring vessels is their need to be self-sufficient throughout an entire voyage. The varying scales of equipment from large aircraft carriers and warships to small commuter boats and fishing vessels require many unique solutions to solve the wide range of applications.

On one side of the spectrum, there are very large ships such as aircraft carriers that operate with a nuclear reactor capable of powering a medium-sized city. Here, nuclear-powered vessels are used to power onboard steam turbines. The tribological issues in turbine engines focus primarily on the journal and thrust bearings that require the development of large hydrodynamic films and the gears used in the speed reduction systems that require lubricants with extreme pressure additives for wear and friction reduction. On the other side of the spectrum, there are relatively small ships that typically operate with a diesel engine of only a few horsepower and have been modified from their original use in automobile engines to work in maritime applications. This section will explore the tribological issues pertaining to maritime lubricants and discuss the challenges presented in maritime diesel engines of these smaller ships.

5.2 Maritime Lubricants

Over the last several decades, diesel engines have become the engine of choice in commercial ships. Maritime diesel engines are powered using fuels that have a higher viscosity index than the traditional automotive diesel engine. A benefit of these fuels is that they have lowered the fuel cost by reducing the necessary refinement. However, this is not without consequences; thicker fuels are more difficult to pump or atomize in the combustion chamber at ambient conditions, and thus, they must be preheated to acceptable temperatures, resulting in higher operating temperatures [56]. In addition, marine fuels are more susceptible to contaminants and increased acidity due to the higher levels of sulfur used as an extreme pressure additive. The high sulfur concentration produces the acidic environment in the engine due to the byproduct of sulfur oxides in the combustion process. Another tribological concern is the suspension of carbon particles in the fuel, which can lead to fouling in the cylinders and cause rings and pistons to stick. Furthermore, abrasive particles matriculate into the engine due to the lack of refinement of the fuel causing an increase in engine component wear rates when compared to traditional fuels used in automotive or aviation diesel engines.

The goal of tribologists and lubrication engineers in marine equipment is to formulate lubricants with the appropriate additives to minimize the acidic effects and reduce the harmful emissions from the combustion process. The importance of minimizing the sulfur oxide and nitrous oxide emissions in maritime engines is a result of their significant environmental impact. Sulfur oxide emissions are generally released in the sea and, through the hydrological cycle, create acid rain [57]. A number of countries are enforcing stringent emission regulations in coastal waters to help combat environmental issues that could potentially harm sensitive ecological systems surrounding many coastal regions [58].

5.3 Maritime Diesel Engines

Maritime diesel engines can be categorized into three groups: high-speed engines operating above 1,000 RPM, medium-speed engines operating between 250 RPM and 1,000 RPM, and slow-speed engines (see Fig. 26.16) operating under 250 RPM [56]. Typically high-speed diesel engines are used in pleasure or sport boats and have engine characteristics similar to automobiles in terms of design, fuel, and lubricants used. Medium-speed maritime engines consist of a four-stroke engine with a high power-to-weight ratio. These engines are used mainly in ferries, container ships, and cruise ships. They use the same fuel as slow-speed engines and have many similar tribological issues. Slow-speed diesel engines are of the two-stroke arrangement and are the largest of the three categories of maritime diesel engines with bore sizes around 1 m and stroke lengths over 3 m. In these engines, the cylinder and crankcase are separated by a diaphragm and stuffing box and the motor directly drives the propeller shaft without the need of a reducing gear or clutch. Slow-speed engines are customarily used in large tankers and passenger liners because of the high fuel efficiency due to their long combustion times and low friction.

The tribological problems that arise in slow-speed engines present themselves when trying to lubricate the separate cylinder and crankcase. The benefit in such a system is that an optimized lubricant can be used for each component without adversely affecting the other. A drawback to having separate lubricant supplies is the requirement of independent preventative maintenance schedules. Solutions to

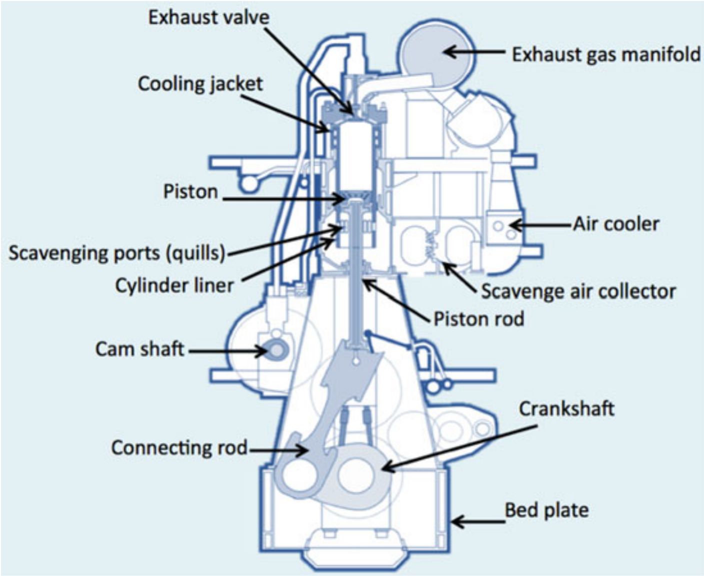


Fig. 26.16 Schematic illustration of a slow-speed (<250 RPM) crosshead diesel engine

slow-speed engine problems often circumvent around lubricant chemistry and coating optimization to thwart corrosion and corrosion-assisted fatigue and wear in the engine due to the acidic nature of the fuels and combustion by-products. Further, problems can develop if lubricant flow rates are too high or low. If over-lubrication occurs, fouling of the cylinder or worse post-cylinder fires can become prevalent, resulting in significant repair costs. Under-lubrication causes the oil to insufficiently neutralize the sulfuric acid and become less effective. The result is periodic wear patterns where significant corrosion fatigue wear and corrosion-assisted abrasive wear have damaged the cylinder liner [59]. To prevent damage against cylinder liners and piston rings, chrome-electroplated and chrome-plated or plasma-sprayed coatings are applied, respectively. Oils in the crankcase lubricate the gears and bearings among other engine components. Within the crankcase, oil leeching through the piston rod diaphragm can become a major concern because it can introduce external contaminants such as cylinder liner wear debris, combustion by-products, and seawater leakage. These contaminants degrade the lubricant's performance and facilitate galvanic corrosion and rusting of tin-based alloys (which are used in journal bearings) producing a black oxide layer. This oxide layer can cause increased asperity contact and higher friction between the bearing and journal resulting in failure. Additionally, the oxide layer can flake off and become a third-body wear particle.

Due to the adverse effects of contaminants in the crankcase, engineers have developed a set of requirements for oils and additives to be used in lubricants, and they are as follows: sufficient viscosity, oxidation and thermal stability, demulsibility, rust and corrosion prevention, antifoaming, detergency, extreme pressure performance, and biocides [60]. It is important that highly refined or high-viscosity-index oils or synthetic oils are used as bases to produce lubricants that have appropriate viscosities for operating at high temperatures. In addition, the oxidative and thermal stability of the oils and additive become a concern because the piston temperature generated during engine operation can be high enough to thermally degrade the lubricant resulting in a loss of viscosity. In the event of seawater contamination, additives are incorporated into the lubricant facilitating emulsification of the seawater in the oil for easy separation. As previously mentioned, rust and corrosion are contributors to wear debris and degradation of components, and thus, the importance of inhibiting additives will extend the lifetime of the engine. Antifoaming additives are used to ensure proper flooding of contacts and pump operation. Detergency additives are included in the lubrication formula because combustion by-products such as carbon- or ash-based soot can foul components and inhibit effective engine performance. During engine operation, many of the contacts occur under high pressure resulting in tremendous friction and wear; extreme pressure additives in the lubricant are used to minimize these affects. The last requirement for lubricants has become prevalent due to biological attacks from organisms that survive in the seawater. The microorganisms reduce the effectiveness of lubricants by clogging filters. Their effects can be minimized by reducing the amount of seawater that leak into the crankcase. Despite the best preventative maintenance, in some instances, this is unavoidable and thus biocide additives must be added to the lubricants to prevent microbial growth. The other solution is that the oil must be heated to a high enough temperature to sufficiently kill the microbes; however, this process can cause thermal fatigue of the oil.

5.4 Conclusions

Many of the tribological concerns with slow-speed engines are also present in medium-sized engines except that often the same lubricant is used to lubricate both the cylinder and crankcase in slow-speed engines. The primary concern of maritime equipment is designing the systems and lubricants to operate and function reliably while meeting the demands of seafaring vessels and maintaining a sense of self-sufficiency throughout an entire voyage. The environment and operating conditions in maritime applications present significant challenges that necessitate the development of chemically modified fuels and lubricants to ensure safe, reliable, and compliant operation. In recent developments, tribologists have begun investigating other maritime tribological issues. One such issue is the study of frictional drag reduction between the outer surface of a ship and the ocean water through the development of surface manipulation techniques such as surface texturing and hydrophobic coatings. As maritime equipment advances, new concerns will undoubtedly arise prompting more innovative solutions to the internal propulsion and lubrication systems or external surfaces of the hull. No matter where the advances occur, tribology will certainly play a role in the progression of marine equipment.

6 Tribology in Gas and Steam Turbines

6.1 Introduction

Gas and steam turbines are variants of the basic turbine engine type used to generate power output in the form of thrust or shaft horsepower. A gas turbine burns fuel to create thrust and is generally found in aircraft engines as turbofans or turbojets to propel an aircraft forward. Steam turbines are extensively used in the power generation industry and on large ships to convert high-pressure steam into shaft (mechanical) power through expansion, which can then be used to produce electricity or shipboard propulsion. Within these turbine systems, there are bearings, seals, and gearboxes that require lubrication to ensure proper operation. Often, the lubricant has three roles: to provide lubrication, to remove heat, and collect contaminants. In these systems, the starvation of the lubricant would cause increased friction and wear in the moving parts, thus generating larger amounts of heat that can have detrimental effects on the turbine performance and create dangerous safety hazards. The tribological considerations involved with gas and steam turbines are directly related to their environmental and operational conditions. Gas turbines used in aircraft must constantly circulate, cool, and filter the oil as it travels through the internals of the engine. Similarly, steam turbines must perform the same tasks as well as deal with corrosion issues due to the presence of water and particles in the lubricant and in the steam. The performance issues associated with gas and steam turbines are also present in wind turbines. Wind turbines similarly suffer from particulate and water contamination that affect critical machinery such as gearboxes, yaw drives, pitch drives, bearings, and filtration systems [61, 62]. Many of these issues are so severe in wind turbines due to their lack of maintenance that failure occurs before their designed lifetime [63]. In the following sections, gas and steam turbine systems will be discussed in detail to provide an overview of the tribological challenges plaguing each of their systems.

6.2 Gas Turbines

6.2.1 Overview

Gas turbines are typically used to power aircraft, helicopters, small ships, power stations, pumping stations, and sometimes in vehicles. Figure 26.17 reveals the various mechanical arrangements of aeroengine gas turbines [64]. Regardless of their application, the construction of a gas turbine is composed of three main systems—the compression, combustion, and turbine systems. Throughout each of these systems, there are ancillary components that are critical to the operation of the turbine. The compression system introduces air into the gas turbine while simultaneously compressing it before the air enters the combustion system where the

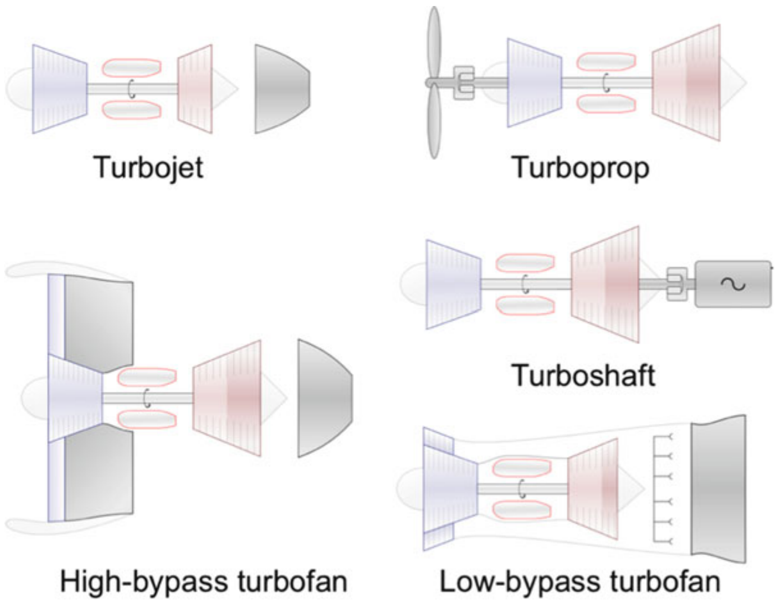


Fig. 26.17 Schematics of various aeroengine gas turbines [77]

fuel-air mixture is burned providing heat energy to the system where the turbine blades can rotate as low as 2,500 RPM and increasing beyond 40,000 RPM providing the necessary power output [64]. Due to the requirements of gas turbines to operate at the highest possible efficiency, the combustion system is designed to operate at the highest temperature possible. The largest restriction that prevents reaching the maximum operating temperature and thus having the highest thermal efficiency is the selection of material in both the combustion and turbine systems. Throughout the gas turbine engine, bearings, gearboxes, and seals are used to ensure that shafts rotate smoothly between fixed parts of the engine's internal structure and lubricants remain in their prospective domains. The bearings and gearboxes generate large amounts of excess heat through frictional heating from the contact between the rollers or balls in the bearing and the bearing inner and outer races or the meshing of the teeth between rotating gears. In an attempt to minimize the heat generation, frictional resistance, and other detrimental effects, oil is supplied as a lubricant into the bearings and gears.

6.2.2 Oil System

The gas turbine lubrication system is a full engine circulatory system that provides lubricating oil to all the necessary rotating assemblies such as gears, drives, and bearings. The purpose of the oil is to remove the excess heat, lubricate the components, and accumulate contaminants and wear debris within the system throughout all operational and environmental conditions and power settings. The lubrication system is designed to provide the appropriate amount of lubricant to each of the rotating assemblies with regard to cleanliness, pressure, temperature, and quantity. This is performed by the oil feed, cooling system, oil return system, and the oil breather (vent) system. Within the lubrication system, heat management is important because one of the pivotal jobs of the oil is to remove excess heat by acting as a coolant. However, as the oil system is circulatory, there must be a subsystem that removes heat from the oil to ensure the oil remains within its thermal operating limits and does not undergo thermal degradation or stress. The subsystem generally utilizes one of two methods for cooling the oil, a fuel-cooled or air-cooled heat exchange system. The fuel-cooled heat exchange system allows the fuel being supplied to the combustion system to absorb the heat through a cross-flow heat exchanger. The air-cooled heat exchange system uses one of two techniques. The air diverted from a compressor is diverted into a heat exchanger, or the air passing over the engine's nacelle is diverted into a heat exchanger. Both of these techniques are similar to the air passing over a car's radiator to cool the oil. A beneficial feature to cooling the oil with the fuel-cooled heat exchange system is that it allows the oil to warm up the hygroscopic fuel and melt any potential ice crystals that may have developed as the fuel sat in the wing tanks while flying at high altitudes. The ice crystals pose a threat by blocking fuel filters or damaging parts of the fuel control system.

6.2.3 Component Lubrication

Due to the high temperatures reached in gas turbines and the extreme rotational speeds, the importance of providing lubricant to the moving components is vital for sustained operation. Ball bearings, roller bearings, and thrust bearings are used to support and allow correct axial rotation of the shafts. Gearboxes are used to provide drive to rotating accessories, power transfer to off-take shafts, and as reducers for drive propellers. Lubricating these components can be performed by three methods: jet feed where oil is directed to the annulus gap in a bearing between the inner and outer races or at the teeth meshing in a gearbox, under shaft feed where oil fed from holes within the shaft to lubricate the inner race surfaces by centrifugal forces, or through splash feed where oil is splashed onto the bearings and gears. An additional feature of the oil is its ability to act as a vibrational damper, where a squeeze film can develop between the outer race and the bearing housing, thereby dampening out any induced vibration. To ensure the lubricant only flows within its system, a series of carbon, brush, labyrinth, ring, and hydraulic seals are utilized to seal the rotating assemblies. As with many seals, degradation can occur in the form of wear and corrosion that can cause oil to leak into other portions of the engine and mix with air resulting in losses of oil. As a precautionary measure, many gas turbines incorporate oil system indicators relaying information about oil pressure, temperature, quantity, and filter blockages that will aid in preventative system maintenance and minimize gas turbine downtime.

6.3 Steam Turbines

6.3.1 Overview

Steam turbines operate by taking steam and feeding it through an inlet casing, throttle valves, and into a turbine. After entering the turbine, the steam expands and accelerates through a stationary nozzle flowing past a series of rotating blades on a turbine where the kinetic energy is converted into torque. The rotary motion of the turbine causes the steam to lose pressure and decrease in temperature, while the torque is used as mechanical energy to power drive machinery. In most cases, the driving machinery consists of generators but can also involve centrifugal pumps, compressors, blowers, and propellers. Steam turbines are typically designed to operate continuously for years at a time without shutting down. Due to the design of a steam turbine, it is vital for the lubricant to be separated from the steam path to prevent contamination of the exhaust steam. This allows for the exhaust steam to be recycled by undergoing condensation and reheating within the system. Moreover, the lack of internal lubrication to the steam path results in relatively low oil consumption [65]. The major components of a steam turbine are the rotor, the stationary parts, the governing and trip systems and valves, and the auxiliary systems such as the lubrication and monitoring systems. From a tribological perspective, the lubrication system and the steam path are important because this is where the majority of the tribological issues affecting friction, wear, lubrication, erosion, and corrosion occur. When these systems are not running at their desired performance levels, they can render a steam turbine inoperable in the worst case.

6.3.2 Tribological Issues of Lubricated Components

Steam turbine lubricating oil performs four functions: (1) lubricate bearings and gears; (2) cool lubricated components by removing excess heat; (3) act as a hydraulic fluid for governor, control valves, and safety devices; and (4) act as a sealant for gas seals. The components in a steam engine that require lubrication are similar to those found in a gas turbine, except in a steam turbine they reside outside the steam path. Proper isolation techniques must be in place to prevent contamination of the steam or contamination of the lubricant by environmental factors. Journal, thrust, hydrodynamic, and rolling element bearings are used to support the rotation of shafts, ensure proper axial positioning of shafts, and support thrust loads that may arise from the steam forces. Within these systems, components are lubricated in the clearance spaces. In a bearing, these clearance spaces occur between the inner race, outer race, and bearing housing. Improper lubrication can cause bearing distress, failure, overloading, insufficient oil flow, insufficient bearing clearance (or endplay), excessive overspeed (or vibration), and high inlet oil temperatures, all of which are detrimental to the bearing, detract from its performance, and limit its operational lifetime. During maintenance inspections, bearings are examined for wear or distress, such as scoring, cracks, pivot fretting, electrostatic discharge, heat discoloration, corrosion, flaking, signs of overheating, contamination of oil in the form of varnish deposits, and loss of babbitt bonds [64]. Other tribological issues involve various lubrication techniques to reduce friction, decrease wear, and minimize thermal expansion, thus reducing the likelihood of binding which can cause distortion, misalignment, and vibration.

Due to the continuous use of steam turbines and the many functions the lubricant plays, it is often necessary that the oil is optimal in regard to chemical, physical, and performance criteria. Oil is modified through the addition of additives to ensure proper viscosity, oxidation stability, freedom from sludge, anticorrosion protection, water separability, air separability, and resistance to foaming [66]. Degradation of the oil can occur from contamination, additive depletion, thermal cycling, oxidation, and bacteriological deterioration. Contamination is an unavoidable occurrence in the lubrication system due to imperfect seals or sealant degradation. The hygroscopicity of the oil causes water to be present in oil at all times whether in free or emulsified forms. The water itself does not pose any problems to the lubricating properties of the oil or have any corrosive effects to components. However, when hot oil cools, water droplets can emerge from the oil [67]. It is these water droplets, which cause corrosion to some metallic surfaces by foaming, sludge formation, or changes in viscosity. Additionally, the water droplets can cause oxidation, additive removal, and bacteriological contamination and reduce the effectiveness of filtration systems. Soluble contaminants such as gases, solvents, flushing oils, preservatives, sealants, and other lubricants can also percolate into the oil; however, they can be removed by vacuum dehydration methods [64]. The normal operation of bearings, journals, gears, and other control mechanisms produce abrasive wear debris that can often contaminate the lubricating oil. If this occurs, flow filtration techniques are required to remove the unwanted contaminants in order to prevent possible failure of components. Additive depletion is a natural occurring phenomenon in lubricants because as additives undergo chemical, physical, or biological reactions, the additive becomes depleted and must be replenished. In some instances, contaminants in the oil react with the additives causing premature additive depletion. Thermal degradation in oil occurs when the oil becomes thermally stressed through the absorption of heat that is often beyond the operating conditions of the oil. Oxidation degradation arises when the oil reacts with the oxygen present in the ambient air. This can cause rust, corrosion, foaming, and poor demulsibility of the oil. Bacteriological deterioration occurs in the form of bacteria or fungal growth in lubricating oils and is the result of biological contamination, high water content, and habitable temperatures. Biological growth in the lubrication system can cause filter blockages and the formation of deposits. Prevention techniques involve the use of proficient cleaning methods, high-temperature sterilizing practices, frequent draining of moisture from the oil, the avoidance of dead legs or noncirculatory areas in pipes, as well as using biocide and antimicrobial additives [68]. Despite the many ways that lubricating oils can deteriorate, by establishing effective preventative procedures, lubricant lifetimes can range from 10 to 20 years or longer with periodic additions of fresh oil [69].

6.3.3 Tribological Issues of Nonlubricated Components

Within the steam path of the steam turbine, there are tribological issues that can arise beyond the scope of lubricants. As mentioned previously, components such as casings, rotating blades, stationary nozzles, seals, valves, and valve guides are nonlubricated components to prevent contamination of the steam. Multiple erosion, corrosion, and wear mechanisms can occur to components in the steam path resulting in loss of power, efficiency, and operation of the turbine. The three prevalent deleterious mechanisms are moisture impingement erosion, erosion-corrosion, and solid particle erosion. Water droplets in the steam cause moisture impingement erosion to the turbine blades as well as compromise the integrity of seals. The result is a change from the optimal thrust loading and a decrease in system performance [70]. Erosion-corrosion problems caused by impurities in the steam develop deposits on the inner surfaces of the steam path such as the casing, nozzles, blades, seals, and sealing surfaces. The deposits may be corrosive if they contain, for instance, chlorine which can lead to pitting and stress corrosion cracking [71]. Other instances of corrosion can develop in geothermal steam turbines due to the presence of mineral constituents and the high acidic levels [72]. When particulates from boiler tubes and steam leads become entrained in the steam, they can lead to solid particle erosion [73]. To prevent steam path erosion and corrosion, it is important to properly condition the steam to ensure reliable operation. This can be done by utilizing separators, moisture removal devices, and strainers upstream and inside the turbine to remove water, contaminants, and particles from the steam. Other solutions to prevent steam path erosion and corrosion involve the use of hardened materials inside the steam path or by providing vulnerable components with corrosion-resistant protective coatings [73]. Other erosive wear mechanisms such as standby corrosion can occur when steam turbines are not in use and suddenly become filled with water vapor due to a valve leak. The stagnant steam can enter the steam path, condense, and cause pitting to various components [74].

6.4 Conclusion

Gas and steam turbines have many tribological issues that plague their performance, reliability, efficiency, and safety. Although a number of performance advancements have been made in gas and steam turbine technology through improved condition monitoring techniques such as magnetic chip detectors, advanced filtration techniques, and lubricant modifiers to aid in the immediate future, there is still a great deal of current and future tribological issues that need effective solutions. Many of the issues that plague gas and steam turbines are now gaining attention in recent decades through the development of wind turbines. Gas and steam turbines as well as wind turbines suffer from particulate and water contamination that affect the performance of gearboxes, drives, bearings, filtration systems, and lubrication systems. In fact, when examining wind turbines, many of these issues are so severe that their components are failing quite rapidly within a few years in contrast to their proposed lifetime of 20 years. As mechanical and tribological research progresses, the various types of turbine technology should improve through the development of corrosion-erosion-resistant materials, improved lubricants, and by better understanding the physical phenomena that plague these systems.

7 Closure

Tribology is a vast field with applications in almost any industry from aerospace to rail transport, from automotive to mining. Understanding of tribological principles is essential for continued success and development of many systems. This chapter sought to shed light upon the interdisciplinary aspects of tribology by portraying the tribological challenges involved in a broad range of macroscale applications and to provide the reader with an accurate portrayal of the science of tribology.

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Exercises

1. Explain the importance of lubricants in space tribology using example of applications.

   Solution: In space tribology, lubrication of moving parts is important to ensure the spacecraft operates at its peak performance and reliability for the duration of a voyage. Examples of space applications include solar array drives; momentum, reaction, and filter wheels; tracking antennas; scanning devices; and various sensors. The Galileo spacecraft is good example of a narrow margin for a potentially expensive tragedy illustrating how the need to develop adequate, sustaining lubricants is pivotal to the success of space tribology.

2. In automotive applications, friction plays a distinct role. Describe two situations where moderate to high friction is necessary for safe operation of a vehicle.

   Solution: The first situation in which moderate friction is necessary is in the tire-road interface. If there is too much friction, the automobile will constantly have to overcome this resistive force to operate, and if there is too little friction, an automobile will have insufficient lateral and directional stability to steer and operate safely. Vehicle brakes are the second situation where high friction is necessary to ensure proper braking power facilitating safe operation. Brakes operate by dissipating mechanical energy by means of friction; thus, if there is not enough friction, an automobile will require more stopping distance; for this reason alone, high friction is necessary.

3. Why is the preservation of the wheel-rail contact vital to the sustainability of the railway transport industry? Briefly explain three deleterious mechanisms that plague railway transport.

   Solution: The wheel-rail contact is vital to the sustainability of the railway transport industry because the largest investment outside of real estate is steel rails. These rails are worn down through the continuous interaction of the steel wheel that rides along them, through four wear mechanisms: adhesion, abrasion, fatigue, and fretting. Adhesion is the bonding of the wheel to the rail in the absence of a lubricant that shears causing damage to both interfaces. Abrasion occurs when the harder material plows through the softer material. Fatigue arises from the cyclic normal and shear stresses produced by the relative motion of the wheel on the rail causes cracks to initiate and propagate through the surfaces resulting in delamination of the surfaces. Fretting is a consequence of low-amplitude vibratory motion between two bodies, either the wheel, rail, or any accumulated wear debris.
4. List three mechanisms that are detrimental to the performance of earthmoving equipment?

   Solution: Earthmoving equipment suffers tremendously from (1) wear, (2) abrasion, and (3) high impact levels. Much of this is due to the growth of the equipment in the mining and mineral processing industries which are progressively developing methods to seek out lower-grade ores, thereby requiring a larger output of raw mineral while simultaneously lowering operating costs, thus making the entire processes economically feasible.
5. What are some of the requirements for oils and additives in marine equipment?

   Solution: Engineers have developed a set of requirements for oils and additives to be used in lubricants in marine equipment, and they are as follows: sufficient viscosity, oxidation and thermal stability, demulsibility, rust and corrosion prevention, antifoaming, detergency, extreme pressure performance, and biocides. Many of the additives are used to minimize lubricant deterioration from seawater contamination, microbes, and other environmental and operational factors.
6. In gas and steam turbines, what are the three pivotal roles of a lubricant?

   Solution: In gas and steam turbines, the three pivotal roles of a lubricant are to (1) provide lubrication to critical mating components, (2) remove heat from frictional interfaces, and (3) collect and remove contaminants from lubricating interfaces.